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MACHINE-LEARNING BASED HOURLY PROBABILISTIC FORECAST OF SEA-BREEZE INDUCED RUNWAY HEADWIND CHANGES AT THE HONG KONG INTERNATIONAL AIRPORT

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1. INTRODUCTION

The Hong Kong International Airport (HKIA) was built on a land reclaimed from a small island called Chek Lap Kok over the western part of Hong Kong. The HKIA is surrounded by seas in the east, north and west, and a large landmass to its south. The diurnal variation of temperature difference between the seas and the airport landmass occasionally triggers a prominent sea breeze circulation at the airport. While the prevailing wind direction in Hong Kong is from the east, the runways at HKIA are oriented in the approximately east-west direction and the onset of sea breezes often leads to westerly winds over the runways during the day [1]. Accurately predicting the evolution of the sea-breeze circulation and the timing of wind direction changes is crucial for efficient air traffic and airport operations, as the runway use for aircraft landing and take-off is primarily determined by the prevailing wind direction over the runways.

Coarse resolution Numerical Weather Prediction (NWP) models cannot always capture wind direction changes caused by meso-scale weather phenomena. Identifying weather elements that contribute to the development of westerly sea breezes at the HKIA will be useful for the prediction. Machine learning techniques are considered a suitable method to provide a quantitative likelihood assessment of the sea breeze effect in hourly intervals. To facilitate operational decision making, a similar approach is adopted to forecast the probability of westerly headwinds/tailwinds on the runway reaching certain threshold. This paper briefly discusses the machine learning models developed for forecasting of sea breeze and westerly headwinds/tailwinds reaching 5 knots on the runway, the initial verification results and several case demonstrations.

2. METHODOLOGY AND STATISTICS

2.1 XGBoost for probability forecasting

Gradient boosting is a machine learning technique for regression and classification problems [2], and XGBoost (Extreme Gradient Boosting) developed by Chen and Guestrin [3] is renowned for its scalability and efficiency in both tasks. Its flexibility allows the algorithm to effectively handle non-linear relationships between input features and the target variable, making it suitable for complex predictive tasks.

In this study, XGBoost is employed to construct the models that forecast the probability of sea breeze at HKIA and the probability of westerly headwinds/tailwinds reaching 5 knots at HKIA (hereafter referred to as 'westerly winds reaching 5 knots' for simplicity). The XGBoost library in Python is adopted for developing the algorithms. The abstract process of model training is illustrated in Figure 1.

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Figure 1. The conceptual diagram for process of model training

In addition, the training process can be summarized as below:

(a) There are two sets of historical data, one is the sea breeze statistics and the other is westerly winds reaching 5 knots on the runway of HKIA. More information about these datasets can be found in Sections 2.2 and 2.3.

(b) The input parameters for the forecasting model include meteorological observations collected daily at 05:00 local time, along with hourly model forecast data generated by the Objective Consensus Forecast (OCF) [4] of the Hong Kong Observatory (HKO). A summary of these parameters is given in Table 1. The input parameters were selected through trial and error, as well as established forecasting practices in order to reduce the training resources.

Observations at 5:00 Local Time	Model Forecast Data
Month of the date	
Sea surface temperature	
Pressure at the aiport	Total cloud amount
Airport temperature	Airport temperature
Wind speed at the aiport	Wind speed around the airport
Wind direction at the airport	Wind direction around the airport
Wind speed at the other stations	Wind speed at other stations
Wind direction at other stations	Wind direction at other stations

Table 1: A summary of input parameters for the prediction model

(c) The training period for the model encompasses historical data and parameters for the period 2017-2022.

(d) The outputs of the models are the probability of sea breeze and the probability of westerly winds reaching 5 knots on the runway in the next 30 hours.

(e) The models are verified against the corresponding data from 2023 to evaluate the model performance in forecasting the probability.

2.2 Sea breeze statistics

HKO has manually recorded instances of sea breeze occurrences and their onset time at HKIA even though the demarcation could be sometime subjective. For sea breeze retreat, the timing is determined based on specific criteria derived from METAR wind direction data. It is said to be retreating when the wind direction changes from an angle between 220° and 350° to an angle between 000° and 210°, with the condition

persisting for at least two consecutive hours, including instances of variable (VRB) winds.

Figure 2 presents statistics from 2014 to 2023, indicating that the onset of sea breeze at HKIA predominantly occurs around 11:00 local time, while the retreat of sea breeze typically happens before 18:00 local time.

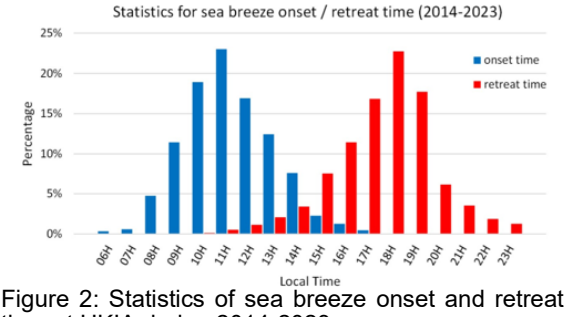


Figure 2: Statistics of sea breeze onset and retreat time at HKIA during 2014-2023

The historical existence of sea breeze at HKIA can be defined as the period between the onset and retreat of the sea breeze. During this period, the prevailing wind direction typically ranges from southwesterly to northerly. Figure 3 shows the distribution on normalized sea breeze existence at HKIA within the day during 2014 to 2023.

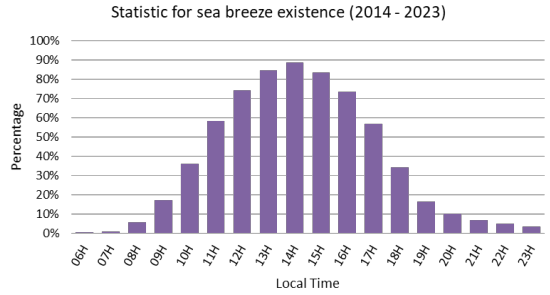


Figure 3. Statistics of sea breeze existence at HKIA during 2014-2023

Land reclamation activities in the northern part of Chek Lap Kok for the Three-runway System at HKIA took place from May 2018 till mid-2022 when the north runway became operational. Given the potential impact of extensive alterations on local meteorological conditions, it is essential to monitor any changes in sea breeze patterns throughout and following the reclamation process. Observations collected during this period showed that the characteristics of the sea breeze, particularly its onset and retreat times, as well as its general pattern, remained similar with historical data.

2.3 Statistics of westerly winds reaching 5 knots

Due to restrictions related to tailwind operations, a change in runway use will be initiated when the direction of prevailing winds changes to the opposite direction. This transition may result in approximately six minutes of air traffic disruption during which no aircraft is directed to land or take off.

In light of these operational constraints, the speed component of winds along the runway orientation is critical. The statistics of maximum 10-minute mean westerly headwind/tailwind reaching 5 knots (westerly winds reaching 5 knots), measured over the course of an hour on the runway of the HKIA, is selected as a critical threshold in the study. In this context, the westerly winds observed are not solely due to the sea breeze effect; it may also be caused by other meteorological phenomena such as the northeast monsoon, and the outer circulation of tropical cyclones. Statistical analysis demonstrates a consistent trend where prevailing winds predominantly originate from an easterly direction. However, as shown in Figure 4, there is a marked increase in westerly winds that occurs during the daytime hours.

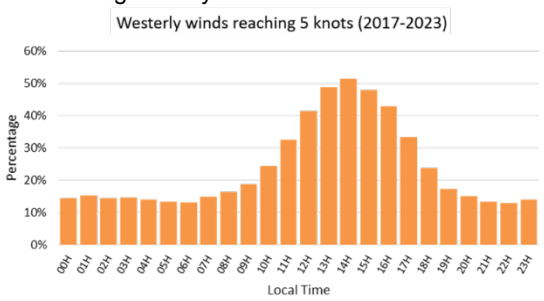
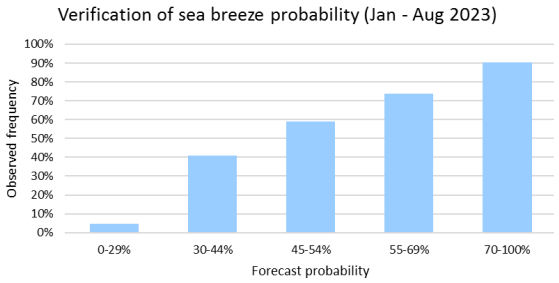


Figure 4: Statistics of westerly winds reaching 5 knots during 2017-2023

3. RESULTS AND VERIFICATION

3.1 Probability of sea breeze

To validate the predictive model for sea breeze occurrences, observational data from January to August 2023 were compared against the model results. The reliability diagram in Figure 5 indicates an appropriate trend for the predicted probabilities of sea breeze events.



	0-29%	30-44%	45-54%	55-69%	70-100%
Total data	6714	375	224	344	475

Figure 5. The observed frequency of sea breeze against forecast probability

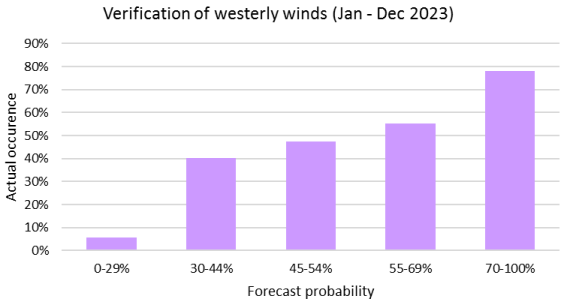
Table 2 shows the verification results for various thresholds (15%, 30%, 45%, 55%, 70%) used to consider the likelihood of sea breeze occurrences. For instance, when a threshold of 30% is applied, it indicates that when the forecast probability is 30% or above, a sea breeze is deemed likely at that particular hour, and the Critical Success Index (CSI) is calculated to be 0.56. The probability of detection (POD) stands at approximately 0.75, demonstrating the model's effectiveness in identifying actual sea breeze occurrences within the forecast hour. Meanwhile, the false alarm rate is noted to be about 0.32.

	Verification				
Threshold	15%	30%	45%	55%	70%
POD	0.88	0.75	0.63	0.53	0.33
FAR	0.46	0.32	0.22	0.17	0.10
CSI	0.50	0.56	0.54	0.48	0.32

Table 2. The verification results for occurrence of sea breeze in various thresholds

3.2 Probability of westerly winds reaching 5 knots

Similarly, full-year data from January to December 2023 were analyzed to compare against the model results for predicting westerly winds reaching 5 knots. The reliability diagram also indicates an appropriate trend between the predicted probabilities and the actual occurrences of westerly winds. This suggests that the model demonstrates skill in providing forecasts regarding westerly winds at HKIA.



	0-29%	30-44%	45-54%	55-69%	70-100%
Total data	11123	881	537	874	2280

Figure 6. The observed frequency of westerly winds reaching 5 knots against forecast probability

Table 3 shows the verification results for occurrence of westerly breeze in various thresholds. For instance, for a threshold of 30%, the verification result reveals a Critical Success Index (CSI) of 0.55, a probability of detection (POD) of 0.82, and a false alarm rate (FAR) of 0.37.

	Verification				
Threshold	15%	30%	45%	55%	70%
POD	0.93	0.82	0.72	0.65	0.51
FAR	0.47	0.37	0.32	0.38	0.22
CSI	0.51	0.55	0.54	0.52	0.44

Table 3. Verification results for occurrence of westerly winds reaching 5 knots in various probability thresholds

3.3 Influence of input parameters on the forecast probability

Figure 7 shows the importance factors of various parameters input to the models for forecasting the probability of sea breeze and probability of westerly winds reaching 5 knots. It is found that the hilltop wind speed at Tai Mo Shan from OCF model (OCF TMS wind speed), the hilltop wind speed of Tate's Cairn from OCF model (OCF TC wind speed) and the forecast hour are the three most significant factors that contribute to the probability of sea breeze prediction. The observations are in line with the forecast experience that significant winds on high ground can disrupt the establishment of sea breeze circulation at HKIA.

For the probability of westerly winds prediction, the wind direction of Tai Mo Shan from OCF model (TMS wind dir), the wind speed of Tai Mo Shan from OCF model (OCF TMS wind speed) and the wind direction at the airport from OCF model (OCF HKA wind dir) are the most significant contributing factors.

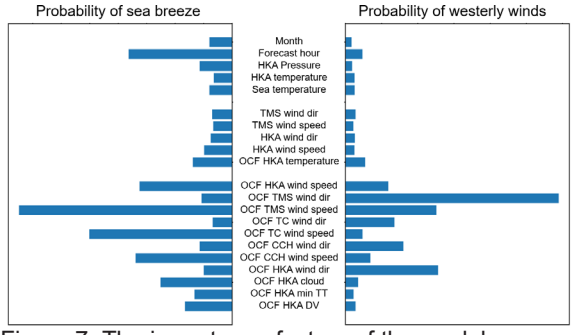


Figure 7. The importance factors of the models

3.4. Case Demonstration

(a) The case on 5 January 2024

Table 4 summarizes the hourly forecast probabilities of sea breeze occurrence, the probability of westerly winds reaching 5 knots, and the actual maximum westerly winds recorded on the runway. The data indicate a significant increase in the probability of sea breeze occurrence starting at 10:00 local time, followed by a marked decrease after 17:00 local time. Figure 8 displays screen captures of wind changes at HKIA at approximately 09:00, 11:00, 14:00, and 18:00 local time, illustrating the progression of sea breeze onset and retreat generally matched with the forecast trend. Furthermore, Table 4 also shows that the probability of westerly winds reaching 5 knots on the runway markedly increases from 11:00 local time and notably decline after 16:00 local time. Actual measurements reveal that the maximum westerly headwind reached 5 knots during the hours from 12:00 local time to 15:00 local time, confirming the model's predictive capabilities.

Forecast Hour (Local Time)	Probability of sea breeze	Probability of westerly winds reaching 5 knots	Actual Max westerly winds within the hour (knots)
06	2%	1%	Nil
07	2%	1%	Nil
08	2%	2%	Nil
09	6%	3%	Nil
10	29%	10%	Nil
11	68%	40%	3.9
12	88%	74%	5.7
13	93%	87%	6
14	93%	85%	5
15	92%	81%	5.9
16	87%	68%	4.7
17	76%	49%	3.7
18	48%	18%	1.4
19	23%	6%	Nil
20	18%	6%	3
21	13%	5%	Nil
22	11%	4%	Nil
23	9%	3%	Nil

Table 4: The hourly forecast probabilities of sea breeze occurrence, the probability of westerly winds reaching 5 knots, and the actual maximum westerly winds recorded on the runway

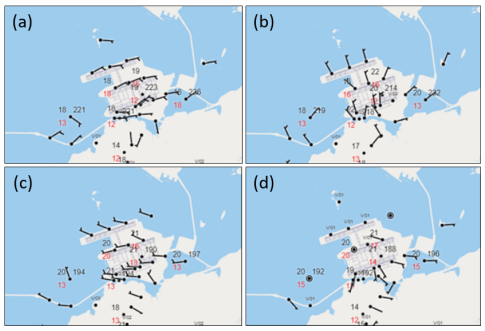


Figure 8. Screen captures of wind changes at HKIA at approximately (a) 09:00 local time, (b) 11:00 local time, (c) 14:00 local time and (d) 18:00 local time on 5 January 2024.

(b) The case on 3 December 2024

Table 5 showed another case demonstration of 3 December 2024. The data indicate that the probability of sea breeze occurrence generally aligns with the observed timing of actual sea breeze onset and retreat, as depicted in Figure 9. Additionally, the probability of westerly winds reaching 5 knots shows notable alignment with the actual measurements of maximum westerly winds recorded on that date.

Forecast Hour (Local Time)	Probability of sea breeze	Probability of westerly winds reaching 5 knots	Actual Max westerly winds within the hour (knots)
06	1%	0%	Nil
07	1%	1%	Nil
08	2%	1%	Nil
09	5%	1%	Nil
10	14%	3%	Nil
11	37%	12%	Nil
12	75%	55%	4.5
13	81%	67%	5.2
14	83%	71%	5.4
15	80%	72%	5.6
16	75%	61%	6.4
17	63%	37%	5.9
18	24%	7%	2.4
19	9%	2%	4.4
20	4%	1%	Nil
21	2%	1%	Nil
22	1%	1%	Nil
23	1%	0%	Nil

Table 5: The hourly forecast probabilities of sea breeze occurrence, the probability of westerly winds reaching 5 knots, and the actual maximum westerly winds recorded on the runway

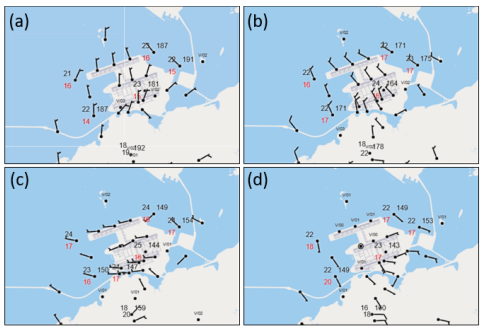


Figure 9. Screen captures of wind changes at HKIA at approximately (a) 10:00, (b) 12:00, (c) 14:00 and (d) 18:00 local time on 3 December 2024.

3.5 Application and future work

The verification method developed in this study provides useful guidelines for Aviation Forecasters and Aeronautical Meteorological Advisers [5] at HKO in evaluating the likelihood of sea breeze occurrences and westerly winds reaching 5 knots at HKIA.

Future work will focus on several key initiatives: enhancing the forecasting model through additional data collection and ongoing verification; launching the probabilistic westerly winds product based on model predictions and forecaster adjustments for users such as Air Traffic Control (ATC) and airlines; and educating users on effective interpretation of the probability forecasts. These efforts aim to improve operational safety and efficiency at HKIA.

4. SUMMARY AND CONCLUSIONS

This paper discusses the development and application of machine learning techniques in the forecasting of sea breezes and westerly winds at HKIA. The machine learning models developed demonstrate the feasibility of predicting wind direction and speed, with the probabilistic forecasts at hourly intervals showed good alignment with actual observations. The predictive models show potential for enhancing early preparedness and decision-making regarding runway use in air traffic operations.

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